

ADVANCES IN TURBULENCE DETECTION AND AVOIDANCE FOR COMMERCIAL  
AVIATION

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59<sup>th</sup> Annual International Air Safety Seminar

Paris, France

October 25<sup>th</sup>, 2006

## 1. BACKGROUND

Aircraft encounters with turbulence are the leading cause of injuries in the commercial aviation industry in the United States. It is estimated that currently there are more than three turbulence-related injuries per day in the United States (Reference 1). Given the projected growth in air travel, this injury rate is expected to double by 2015. This is not a phenomenon restricted to the United States. Airline operations in many other areas of the world are affected by turbulence. Over half of all airline accidents on scheduled flights occurring in Japan over the past 20 years have been due to turbulence [Reference 2].

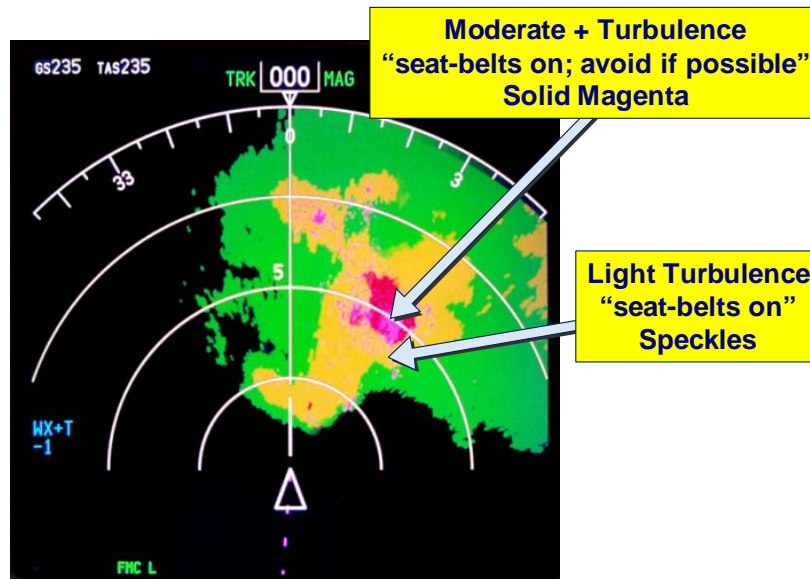
In 1998, the National Aeronautics and Space Administration (NASA) set a goal to reduce the number of injuries due to turbulence by 50% by 2007. Under the auspices of NASA's Aviation Safety and Security Program (AvSSP), two technologies have been developed to detect and assist crews in avoiding turbulence. These technologies were developed to give users on the ground and in the cockpit better information about the location and severity of turbulence. The two technologies are the Turbulence Auto-PIREP System (TAPS) and the Enhanced Turbulence Mode Radar (E-Turb). Widespread implementation of these technologies will go a long way to achieving NASA's stated safety goal.

As described below, both of these technologies can be implemented within today's infrastructure, and will benefit from planned improvements in datalink communications, avionics, airspace management, and cockpit displays.

### ***1.1 E-Turb Radar***

This E-Turb radar uses advanced algorithms to improve the airborne radar detection of turbulence in and around convective activity. Although many of today's airborne weather radars have a turbulence mode, the current system creates so many false, missed, and nuisance predictions that it is not widely trusted or used by pilots. Under the NASA AvSSP, a new technique of processing the radar measurement was developed and tested that scales the measurement to display the predicted g-loads that will be experienced by the aircraft. In keeping with how turbulence has been displayed on legacy systems, areas of potential hazard are represented on the radar display by the color magenta. Somewhat different from the conventional turbulence mode is the

display of two-level turbulence hazard on the E-Turb display as shown in Figure 1. The speckled magenta (representing light-to-moderate turbulence) indicates to the pilot that if were to transit that region the seatbelt sign should be on. The solid magenta area (representing a region where there could be moderate or greater turbulence), the seatbelt sign should be on and that the region should be avoided if possible.



**Figure 1: Two-Level E-Turb Radar Display**

The E-Turb radar algorithms were installed on a Rockwell Collins WXR-2100 MultiScan<sup>SM</sup> radar and have been flying on one Delta Air Lines B-737-800 (also equipped with TAPS – see below) since August 2004. The turbulence hazard information provided by the E-Turb radar display has received very positive feedback from Delta Air Lines’ pilots (see Section 3 below).

## 1.2 TAPS

The TAPS is a combination of non-flight critical software applications (residing in an aircraft's computer system and on ground station computers) that 1) automates the reporting of all significant (aircraft) encounters with any kind of turbulence, 2) enables the interpretation of the turbulence reports for other aircraft, and 3) displays the turbulence information in the cockpit and on the ground for use by aircrew and ground based personnel (operations, safety, and maintenance). TAPS provides, via data link, quantitative turbulence hazard information from which pilots, dispatchers, and controllers can quickly and easily understand the impact that reported turbulence may have on aircraft. The architecture of TAPS is illustrated in Figure 2. Aircraft #1 encounters some form of turbulence. Turbulence measurement algorithms on board the aircraft decide whether the turbulence was significant enough to transmit a report.

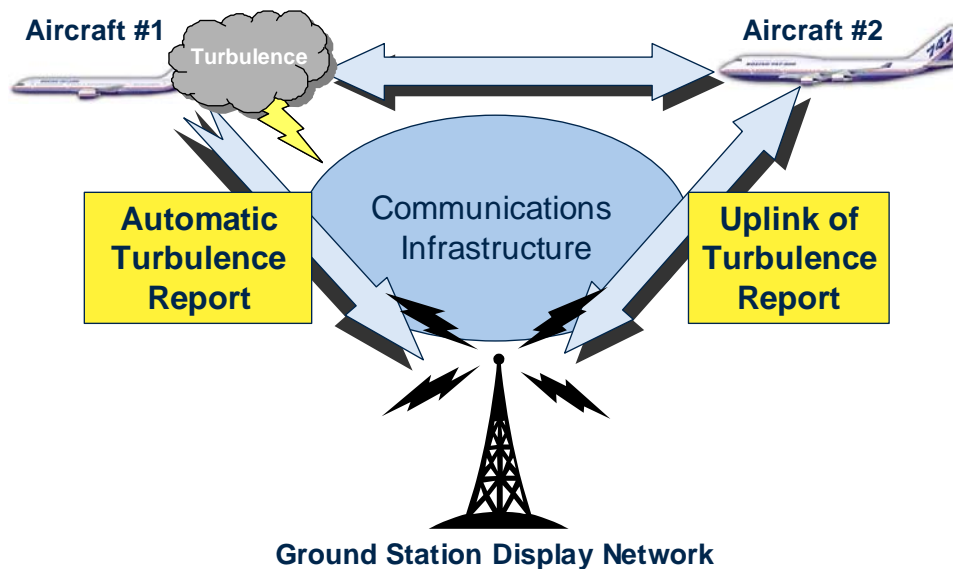
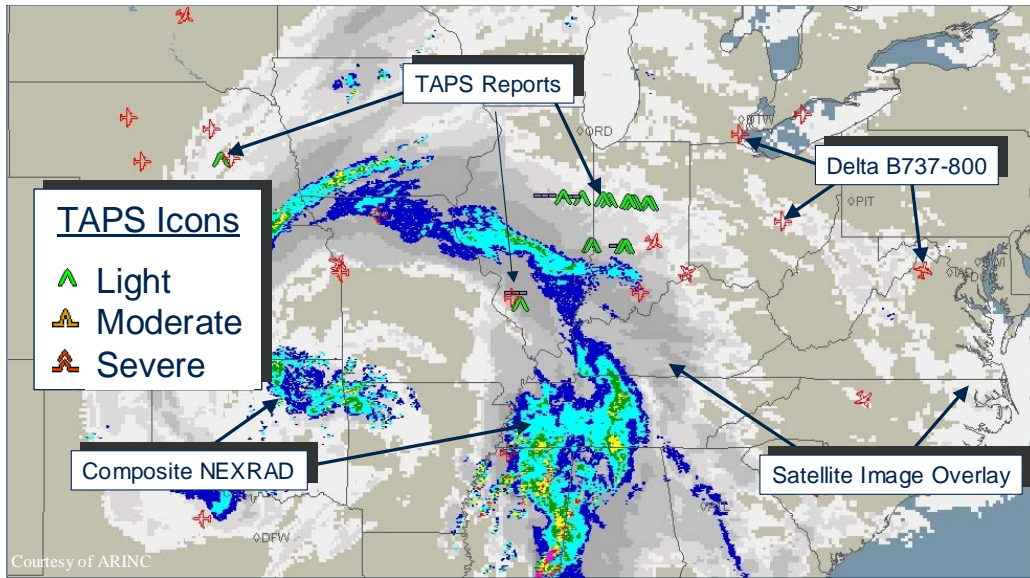


Figure 2: TAPS Architecture

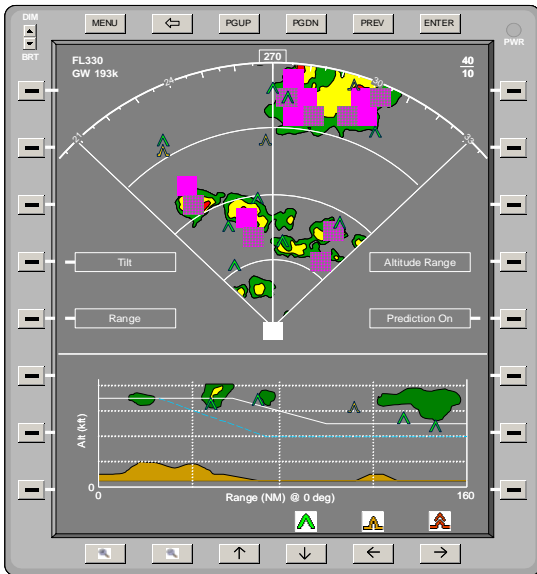
If the encounter is significant enough, a report comprised of a packet of data is generated (see Section 3.2 for more discussion of the content of the report). This data packet is transmitted to the ground, stored in a database, and displayed on a ground station. The data packet is also transmitted to other aircraft (Aircraft #2), either directly from the originating aircraft or uplinked from the ground-station. The receiving aircraft will, using an interpretation algorithm, scale the data for its aircraft type and current state (altitude, speed, weight, etc.). If the turbulence hazard is significant for the second aircraft, the information will be displayed on a cockpit display. The turbulence icons on the cockpit display would be colored according to the severity of the threat to the receiving aircraft (not the severity of the turbulence encountered by the reporting aircraft). The scaled graphical reports are designed to enhance the situational awareness of flight crews not only to the location of turbulence hazards, but also to the severity and potential impact of the turbulence hazards on their aircraft.

Ground displays of the TAPS reports will be accessed via the Internet, and can be incorporated with other information such as the Aircraft Situational Display, NEXRAD, and satellite images. The ground display is available and being used today. An example display is shown in Figure 3.

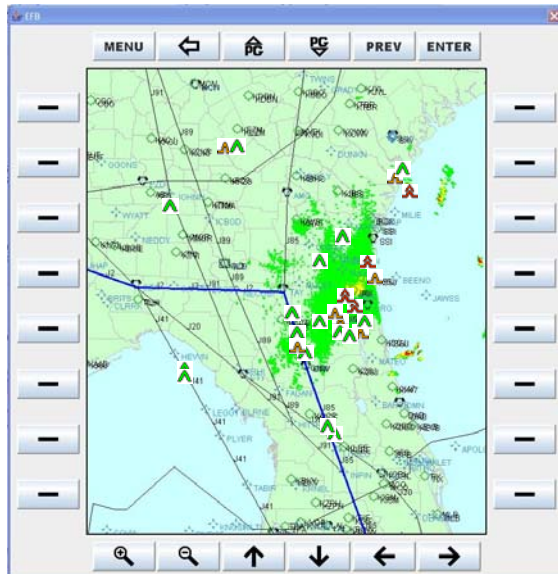


**Figure 3: Example of a TAPS Ground Display on ARINC’s WebASD<sup>SM</sup>**

Cockpit displays of TAPS information can be integrated with other systems (e.g., radar). Figure 4 shows two different types of display being developed. The display on the left, (a), illustrates TAPS and E-Turb radar information being merged onto an aircraft’s navigational display. The display on the right, (b), shows how TAPS might look on a Class II Electronic Flight Bag (EFB).



(a)

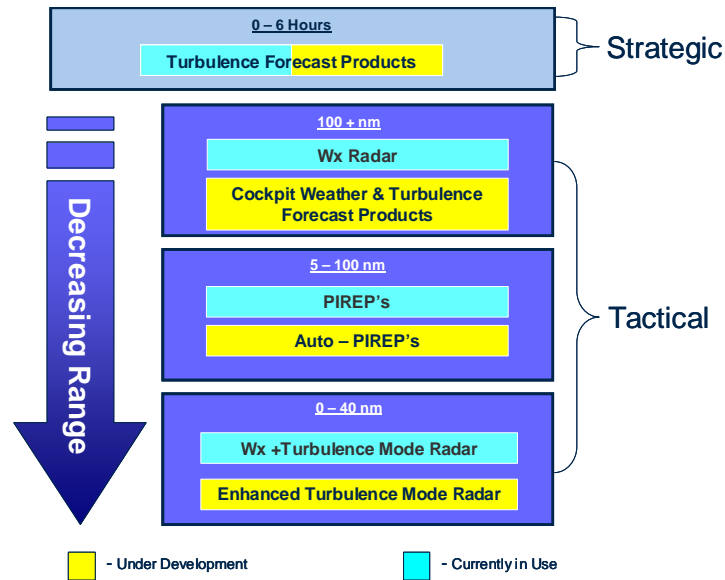


(b)

**Figure 4: TAPS Cockpit Display Concepts**

### **1.3 Concept of Operations**

A fundamental concept in the application of turbulence awareness information is the “seamless hierarchy” of turbulence technologies. This is illustrated in Figure 5. There are products either currently available or under development which will give stakeholders (pilots, dispatchers, Air Traffic Control (ATC)) turbulence information with varying time and distance horizons. Forecasts will provide information on the potential for turbulence for some period of time in the future. The forecasts can be used for flight planning – the so-called “strategic” applications.



**Figure 5: Hierarchy of Turbulence Products**

On the flight deck, the weather radar can provide reflectivity information over 300 NM (depending on the radar system). Although there is no direct correlation between reflectivity and turbulence, reflectivity (like turbulence forecasts) can give an idea of where potential turbulence may exist. In the future other cockpit weather products displayed on an EFB may provide other weather information over similar distances.

Today, manually generated PIREPS (typically verbal over the ATC frequency) currently provide the pilots with turbulence information in a very subjective manner. TAPS will complement these products to improve the turbulence encounter reporting information. At ranges up to 40 NM, the E-Turb function on the radar will provide real-time turbulence information with a warning time of up to five minutes ahead of the aircraft.

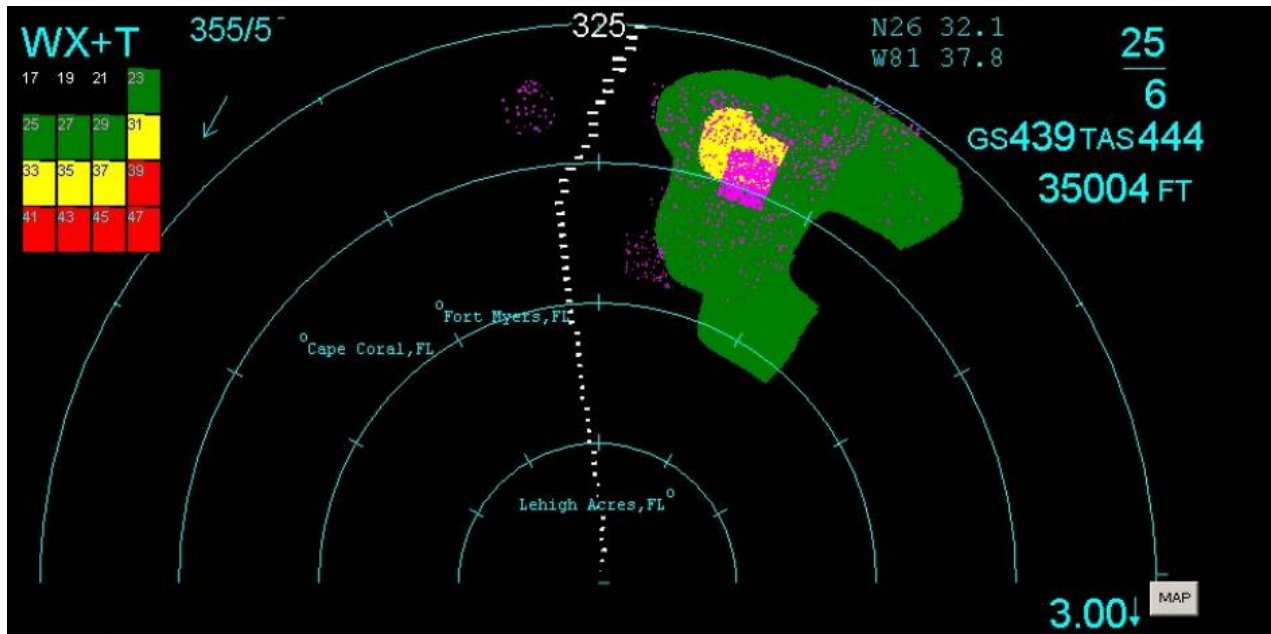
## **2. THE CURRENT IMPLEMENTATION AND USES OF TAPS AND E-TURB**

As the system was developed under a NASA program, its current implementation focuses on the application and use of the technologies in the United States. The envisioned international implementation and applications will be presented in the next Section.

### ***2.1 E-Turb Radar***

The E-Turb Radar was installed on one Delta Air Lines B-737-800 aircraft (also equipped with TAPS). The radar was also equipped with a data logging capability built into it that allows turbulence detection data to be stored and downloaded from the aircraft at a later date. The stored data comprises radar reflectivity and turbulence scans, as well as flight data. Memory limitations required that the radar scans were recorded at a lower resolution than would have been seen in the cockpit. This data logger has provided an extremely useful tool to replay events and to perform statistical analyses of the radar's performance.

Two examples of the radar performance are presented below. Figure 6 shows the aircraft position at the bottom of the screen and a "snapshot" of the subsequent flight path by the white dotted line. Regions of reflectivity are shown by the green and yellow areas, and the turbulence regions are shown by the speckled and solid magenta. The shapes of these regions are affected by the reduced resolution of the images due to the data logger.



**Figure 6: Example of E-Turb Radar Scan - 1**

A region of moderate or greater turbulence can be seen inside the reflectivity region. More importantly, regions of light-to-moderate turbulence (speckled magenta) are seen near the edges and outside of the green reflectivity region. The slight curve in the flight path around the speckled region outside the reflectivity is an indication (of many seen on other flights) that the flight crews are using the radar to maneuver around a displayed turbulence hazard.

Another example is shown in Figure 7. Here there are several regions of turbulence hazard to the right of the aircraft's flight path, one of them being moderate or greater. Although the aircraft is not affected by these regions, this image illustrates what may constitute a typical turbulence encounter leading to an accident; an aircraft maneuvering around convective cells (note the reflectivity region in the bottom left), and flies into

strong turbulence unexpectedly in an area with no reflectivity or hazard showing on the radar.

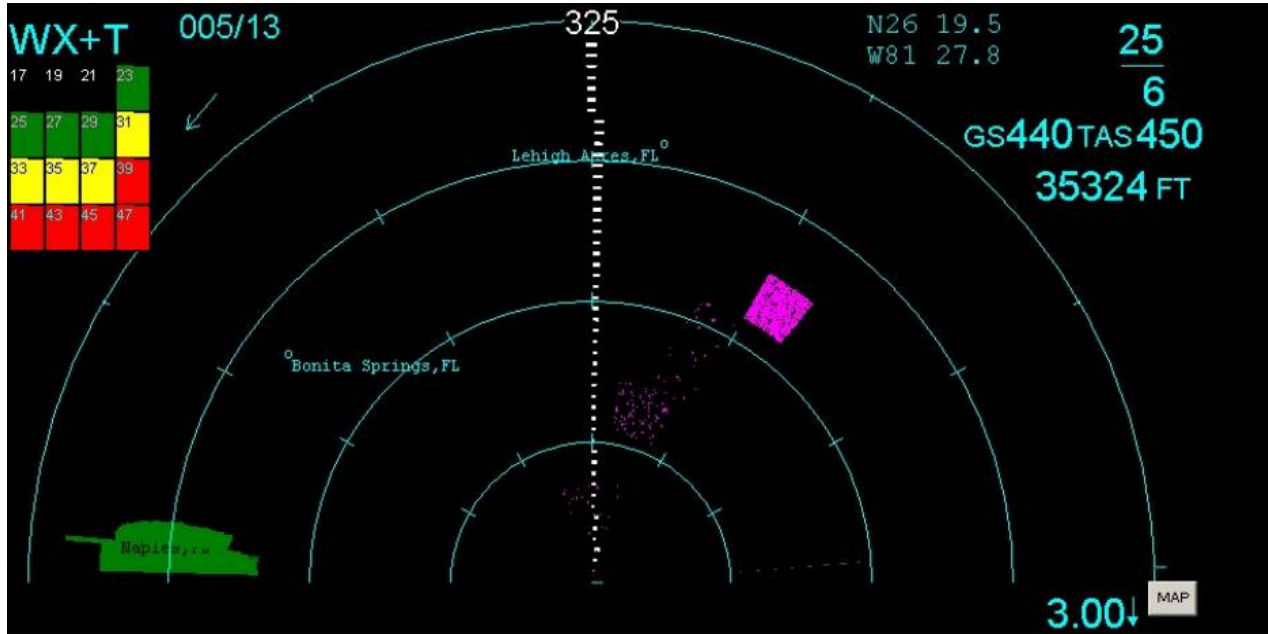


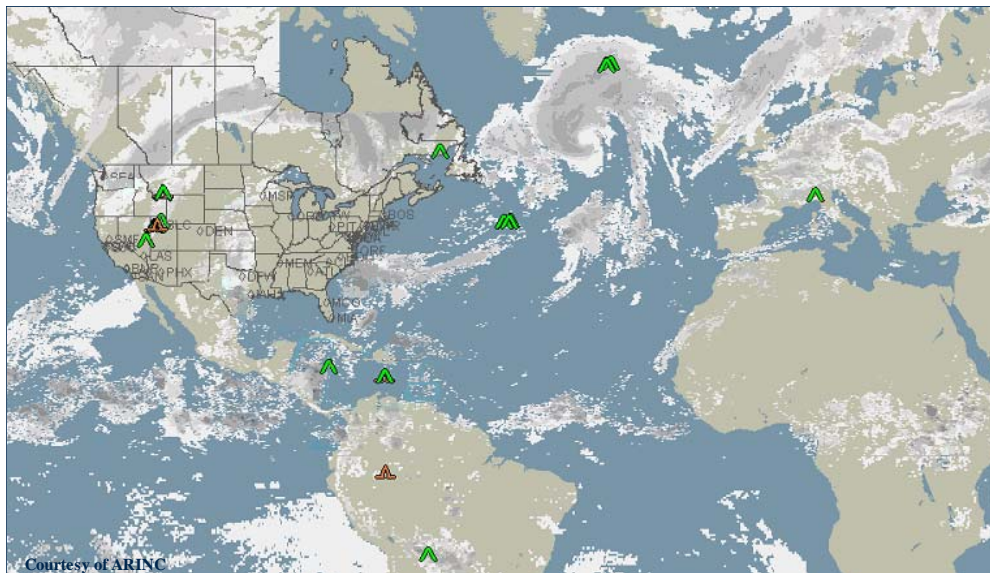
Figure 7: Example of E-Turb Radar Scan - 2

## 2.2 TAPS

Since July 2004 the TAPS algorithms have been installed on 123 Delta Air Lines aircraft (B737-800, B767-300ER, and B767-400ER) for an operational evaluation of the system. The algorithms, reporting logic, and transmission have all been verified using the Aircraft Communications Addressing and Reporting System (ACARS) network. Display of the TAPS reports at a ground station has also been accomplished using ARINC's WebASD<sup>SM</sup> flight-following software as a platform.

The ground display is accessed via the Internet, and is incorporated with other information such as the Aircraft Situational Display, NEXRAD, and satellite images. The

Delta B-767-300ER fleet is used on its international routes, and TAPS reports have been received from all geographic locations where Delta flies (Hawaii, North America, the Caribbean, South America, Europe, Russia, and India). An example is shown in Figure 8 demonstrating that the infrastructure (sensors, databuses, computers, communications) is in place today to realize an international implementation of TAPS.



**Figure 8: TAPS Reports Across a Wide Geographical Area**

Delta Air Lines' dispatchers have been able to access this data and interact with the display. The information received on this display can be assimilated by the dispatcher and then sent up to the cockpit via standard ACARS text messages.

### **3. THE ENVISIONED IMPLEMENTATION AND USES OF TAPS AND E-TURB**

This Section will describe how the systems' implementation is envisioned both in the United States and Internationally. The need for improved safety information for turbulence avoidance is not limited to any one region of the world. This section is

intended to describe approaches and technical barriers to a truly worldwide implementation of TAPS and E-Turb technologies.

### **3.1 E-TURB Radar**

The implementation of the E-Turb Radar will take place in two forms:

- 1) New aircraft, which will have the avionics architecture such that the real-time weight of the aircraft can be accessed by the radar computer, will have installed the E-Turb algorithms tailored to that aircraft type. This is the most accurate form of the E-Turb detection algorithm and will be particularly important for long-haul aircraft whose weight will vary considerably from takeoff to landing.
- 2) For new aircraft that cannot provide weight in real-time to the radar computer, an approximate generic E-Turb algorithm will be installed. This software will contain an algorithm that does not take into account the aircraft's specific type and configuration, but makes an estimate based on statistical techniques. This algorithm is currently in development under a NASA contract.
- 3) Older aircraft that are currently equipped with suitable radar platforms could be retrofitted with the software algorithm in paragraph (2) above. There are some requirements on the capabilities of the platform (computing power, antenna operation, etc.), which may limit the particular radars on which the software could be installed, however there are many systems currently in service that could be candidates.

The different possibilities allow for a significant number of radars to be equipped with the E-Turb capability, obviously depending on the ability of the business case to be made. It should also be noted that although the algorithm that uses the real-time weight will be more accurate than the one that uses a statistical estimate, both will be required to satisfy a Minimum Operational Performance Standards (MOPS) set forth in a Federal Aviation Administration (FAA) Technical Standards Order (TSO) currently under development.

### **3.2 TAPS**

#### **Report Content**

Currently TAPS reports contain the following parameters:

- Time
- Latitude, longitude, and altitude
- Turbulence hazard metric
- TAPS scaling constant (for use in scaling to other aircraft)

as well as other aircraft flight parameters and measured data taken from aircraft sensors. This is the parameter set that was decided upon with Delta Air Lines prior to beginning the in-service evaluation. An industry group will be convened in the next year to define the final form of the report.

Of course some of the data contained in a TAPS report will remain proprietary to the airline from which it originated. For example, whereas an airline will want to know the

gross weight of their aircraft at the time of a turbulence encounter (for maintenance considerations), they would not want this information to be shared amongst other airlines. Therefore only the first five parameters above will be shared. The TAPS reports would either be sent directly to an airline which would strip out the proprietary information and send the “pared-down” reports to a central database, or the reports will be stripped at a central server and disseminated to the airlines with the originating airline receiving the full report. Either way, these processes will be completely automated and will not add any latency to the process.

### **Report Collection, Dissemination, and Display**

An important consideration to receiving TAPS reports worldwide is the datalink coverage and capability. This of course depends on two things: aircraft equipage and infrastructure coverage. Ideally all TAPS equipped aircraft should be able to make reports anywhere on their flight. However, in the recent Delta Air Lines implementation, some aircraft were not equipped with satellite communications equipment. As a consequence, over some regions of oceanic operations TAPS reports that were generated had to be stored on the aircraft until it was within range of a ground station when it was downlinked. This sometimes resulted in significant delays in getting the reports to the ground. This is not a limitation of TAPS, but it does result in a degradation of the system’s performance. Also, there are some regions of the globe where satellite and ground network coverage is such that reports cannot be made regardless of aircraft equipage. Advances in the communications infrastructure continue to reduce the size of

these regions; however, the degradations to TAPS information due to these constraints must be duly noted and considered in a worldwide integration of TAPS.

It is envisioned that the reports from aircraft worldwide will be collected in a central database or server. From there, the reports can be stripped of their proprietary information and prepared for dissemination to users. The reports may be made available in the raw form for incorporation into other applications such as flight-following software platforms. There are several of these platforms on the market, and some US airlines have their own in-house proprietary versions. The raw feed of TAPS reports can be provided for ingestion into these platforms. Other users may want to access the reports already graphically displayed in a similar manner to those images presented earlier on ARINC's WebASD<sup>SM</sup> platform (Figures 3 and 8). The database servers may actually reside in several locations worldwide depending on demand, and routing costs. For example, there may be a requirement for a database server in Asia and one in North America. Either way, the infrastructure requirements are not burdensome.

The TAPS reports will also need to be incorporated into ATC displays. The form of this display will depend on the ATC center, specific country/regional requirements and regulations, and operations. In many cases the TAPS reports will be incorporated into auxiliary decision support displays and not the primary controller's display.

Reports will be also transmitted to aircraft for display in the cockpit. The uplink transmission will be automated by ground station software. As new reports are made, they will be uplinked to aircraft based on their location and other considerations. Reports can also be uplinked "manually" by dispatchers if necessary. The uplinked

reports can be displayed in the cockpit in a number of different graphical formats. The two most likely are:

- i) A Class II or III EFB. The TAPS reports can be overlaid on other weather observation and forecast products. In the coming months, under a NASA contract, TAPS on a Class II EFB will be evaluated in revenue service.
- ii) Integrated with the E-Turb radar display on the aircraft's navigational display. This will allow TAPS reports at longer-ranges to give pilots awareness of the upcoming turbulence hazard regions, while the E-Turb radar takes over within 40 miles to identify the dynamic turbulence "hotspots" within convective activity. AeroTech is currently developing this display with NASA support. Due to hardware and regulatory issues, the implementation of this approach may take longer than the approach (i) above.

### ***3.3 The Total System Concept***

So far this paper has presented two turbulence detection and reporting technologies and a potential information dissemination process to get the information to pilots, dispatchers, and ATC. The full benefits of TAPS and E-Turb will only be fully realized when all the constituents incorporate the information into their decision-making processes. Aside from increasing safety by reducing the number of injuries caused by unexpected turbulence encounters, some examples of realizable benefits include:

- Reduced radio frequency congestion: in regions of high density traffic and/or dynamic weather the use of these technologies will give the pilots and controllers very similar pictures of the location of the turbulence hazards. Verbal requests by pilots to controllers (and vice versa) for reports will not be required, and all that will be carried on the radio will be the altitude or route change requests and clearances.
- More efficient flight planning: knowing where the hazards are and combining them with suitable forecast products will allow dispatchers to identify intensifying/decaying regions of turbulence and plan flights accordingly instead of avoiding large regions of weather completely. Turbulence is typically very localized and better reporting and forecasting will help in the flight planning tasks.
- More efficient flight operations: quantitative knowledge of turbulence severity and extent at altitude will allow pilots to decide on whether to request an alternate cruise altitude instead of getting established at the initial cruise altitude, experiencing turbulence, and then “hunting” for a suitable altitude. Alternatively, a pilot experiencing turbulence at altitude may be willing to endure the turbulence if it is not unsafe, the cabin is secure, and he has some knowledge of the severity and extent of the turbulence. This knowledge may dissuade him from automatically seeking a lower altitude unnecessarily and incurring greater operational costs due to the less than optimal fuel burn at the lower altitude.

- More efficient use of airspace: currently in the United States it is not uncommon for a large region of convective activity to effectively shut down a large block of airspace. This decision is not based on where the turbulence hazards are, but on radar reflectivity (e.g., the composite NEXRAD mosaic). The incorporation of the TAPS reports, improved forecasting, and the adoption of the E-Turb technology on aircraft will allow ATC to grant access to these regions to suitable equipped aircraft with no decrease in safety, thereby precluding the long and often unnecessary deviations around the affected regions.

#### **4. SUMMARY**

Two technologies have been developed that may help in improving the detection and avoidance of turbulence hazards. If widely adopted and implemented, it is expected that they will have a significantly positive impact in reducing the number of turbulence injuries and improving operational efficiency of aircraft. The technologies can be readily implemented in today's aircraft and supporting infrastructure, and can take advantage of improvements and developments planned for the coming years. In addition, the full benefits will only be realized with close collaboration and data sharing between pilots, dispatchers, and ATC.

#### **5. ACKNOWLEDGEMENTS**

Images of the TAPS display and WebASD<sup>SM</sup> are shown courtesy of ARINC.

## 6. REFERENCES

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